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MODEL FOR ULTRAFAST CARRIER SCATTERING IN SEMICONDUCTORS

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Develop microscopic-level many-body models to fully describe coherent optical interactions in the strong-coupling regime with nonlinearly-driven carriers. The model assumes strong electric fields for modeling/simulation of hybrid quantum devices.

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1. Overview

One of the major products the AF is looking for is a lightweight, reconfigurable electro-optic sensor system. Towards that end, we are investigating the possibilities of incorporating a protection layer, an optical signal amplification layer, a detection layer, a solid-state cooling layer, and a readout electronics layer all monolithically integrated within a single pixel of a semiconductor focal plane array (for vast reductions in size and weight). When completed, the microscopic theory that arises from this project will be applicable to each of the various layers of the super-pixel device for both further understanding of the quantum mechanical processes involved, as well as for greatly improving the performance of each layer. This theory will be applied to quantum-kinetic studies of laser damage of semiconductor photodetectors, in order to describe and understand all radiation damage mechanisms so that methods of mitigation can be developed for the protection layer of the monolithic sensor. This theory will be applied to describing and predicting the optical control of scattering-induced dephasing for optical signal amplification in photodetectors using electronic quantum interference, as well as for noise reduction in both detectors and electronics. This theory will be applied to the photo-carrier generation and transport processes involved within the detection layer, for improving performance by minimizing dark-current noise. This theory has already been applied to photoluminescent cooling of detectors; a vibrationless, low-cost, extremely low-volume and weight on-chip solid-state cryogenic cooling scheme for space sensors. Finally, this theory will be applicable to high-power and ultrafast electronics development.

2. Objective

Develop microscopic-level many-body theory to fully describe coherent optical interactions in the strong-coupling regime with nonlinearly-driven carriers under a strong electric field for modeling/simulation of hybrid quantum devices.

3. Approach

1. Develop force balance equation to describe high-field nonlinear transport of hot-carriers in the absence of optical coherence.
2. Couple the force balance equation with a Fokker-Planck equation including optical dissipation to describe high-field nonlinear transport of hot-electrons interacting with an intense optical field.
3. Develop a Boltzmann scattering equation to describe ultrafast scattering of hot-carriers with phonons, impurities, defects and other carriers after excited by an optical field. Demonstrate that a second-order expansion of the scattering equation results in the Fokker-Planck formalism.
4. Use a simplified version of the Boltzmann scattering equation, plus an energy-balance equation, to study photoluminescent cooling of semiconductors.
5. Couple the Boltzmann scattering equation (relative motion) with the force balance equation (center-of-mass motion). Using momentum dissipation for the frictional forces allows carrier heating without the need to introduce electron and lattice temperature definitions for a quasi-equilibrium state, allows the description of physical process for extreme non-equilibrium.
6. Use self-consistent-field approach to fully incorporate many-body effects of electron screening, vertex correction and exchange interaction in semiconductor Bloch equations, allowing us to study the dynamics/quantum kinetics of induced optical coherence in the presence of electron-impurity, electron-roughness, electron-phonon, and electron-electron scattering.
7. Incorporate effects of both carrier quantum kinetics and force balance of photo-excited hot carriers into generalized semiconductor Bloch equations, allowing us to incorporate energy transfer between semi-classical carrier drift-diffusion under an electric field and quantum kinetics of interband/intersubband transitions.

4. Results

4.1 FY04 & FY05

Coupled energy-drift and force-balance equations which contain a frictional force for the center-of-mass motion of electrons were derived for hot-electron transport under a strong dc electric field. The frictional force was found to be related to the net rate of phonon emission, which takes away the momentum of a phonon from an electron during each phonon-emission event. The net rate of phonon emission is determined by the Boltzmann scattering equation which depends on the distribution of electrons interacting with phonons. The work done by the frictional force was included into the energy-drift equation for electron relative scattering motion and was found to increase the thermal energy of the electrons. The importance of the hot-electron effect in the energy-drift term under a strong dc field was demonstrated to reduce the field-dependent drift velocity and mobility. The Doppler shift in the energy conservation of scattering electrons interacting with impurities and phonons was found to lead to an anisotropic distribution of electrons in momentum space along the field direction. The importance of this anisotropic distribution was demonstrated through comparison with the isotropic energy-balance equation, from which we found that defining a state-independent electron temperature became impossible. To leading order, the energy-drift equation was linearized with the distribution function by expanding it into a Fokker-Planck-type equation, along with the expansions of both the force-balance equation and the Boltzmann scattering equation for hot phonons.

The use of a Boltzmann transport equation with a drift term is physically incorrect for optical-field frequencies. Also, the use of a simple energy-balance equation was found to lead to an inaccurate estimation of electron temperature. Therefore, in a second paper, we established a Boltzmann scattering equation for the accurate description of the relative scattering motion of electrons interacting with an incident optical field by including impurity- and phonon-assisted photon absorption as well as Coulomb scattering between two electrons. Multiple peaks on the high-energy tail of a Fermi-Dirac distribution were predicted and the effect of pair scattering was analyzed. Moreover, the effective electron temperature was calculated as a function of both the incident-field amplitude and the photon energy so that the thermodynamics of hot electrons could be investigated.

We next applied the above preliminary theory to the description of photoluminescent (or "laser") cooling in semiconductor heterostructures. A successive four-step model was proposed for spatially selective laser cooling of carriers in undoped semiconductor quantum wells. The four physical steps include the following processes: (1) cold electrons with nearly-zero kinetic energy are initially excited across a bandgap in a coherent and resonant way by using a weak laser field; (2) the induced cold carriers in two different bands are heated via inelastic phonon scattering to higher-energy states above their chemical potentials; (3) the resulting hot electrons and holes radiatively recombine to release photons, thus extracting more power from the quantum well than that acquired during the weak pump process; and (4) hot phonons in two surrounding hot barrier regions thermally diffuse into the central cool quantum well, thereby

cooling the entire lattice with time. Based on this model, a thermal-diffusion equation for phonons including source terms from the carrier-phonon inelastic scattering and the thermal radiation received by the lattice from the surrounding environment was derived to study the evolution of the lattice temperature. At the same time, an energy-balance equation was applied to adiabatically find the spatial dependence of the carrier temperature for a given lattice temperature at each moment. We found a 'V'-shape feature in the carrier temperature that could be predicted by numerical calculations, and became apparent only for an initial lattice temperature above 150 K. We also found a thermal-drag of the carrier temperature as a result of the strong carrier-phonon scattering. The difference between the lattice and carrier temperatures resulting from the thermal-drag effect was larger in the barrier regions than in the well region.

We next established a generalized nonlocal energy-balance equation for excited carriers and phonons for studying the laser cooling of a lattice of wide-bandgap semiconductor such as AlN using a He-Ne laser through a three-photon nonlinear excitation process. The power-exchange densities of the system were calculated and compared for different strengths of the excitation field. When the power-exchange density is positive, it implies laser cooling of the lattice. The effects of initial lattice temperature and field-frequency detuning on the laser-cooling phenomenon under the three-photon nonlinear excitation process was described. The power-exchange densities were compared for both laser cooling and heating using linear and nonlinear excitations. We found that the linear excitation seems more favorable than the nonlinear excitation for laser cooling. However, the resonant three-photon nonlinear absorption will allow the use of a common He-Ne laser for laser cooling of the lattice in AlN, instead of a more expensive ultraviolet laser.

4.2 FY06 & FY07

We proposed a dynamical model for exploring a novel many-body-effect driven optical carrier cooling in steady state based on coupled density and energy equations. We employed these coupled dynamical density and energy equations to search appropriate laser photon energies and intensities that demonstrated a steady-state optical carrier cooling mediated by non-thermal electron-hole plasmas in an intrinsic semiconductor with a lattice temperature fixed by an external heat bath. This dynamical carrier-cooling process is mediated by a photo-induced non-thermal electron-hole composite plasma in an intrinsic semiconductor under thermal contact with a low-temperature external heat bath. The important roles played in optical cooling of carriers by the many-body effects such as bandgap renormalization, screening, and the excitonic interaction, are fully analyzed and explained through the calculations of optical absorption, spontaneous emission, and carrier-phonon scattering. By adjusting the laser photon energy just above the unscreened exciton energy with a very low laser intensity, we predict a crossover with increasing laser intensity from optical carrier heating to optical carrier cooling. On the other hand, by setting the photon energy just below the bare bandgap energy of an intrinsic semiconductor, we predict an opposite switching behavior with increasing laser intensity from

carrier cooling to carrier heating.

Auger recombination was neglected in our calculations because of the low lattice temperatures and low photo-carrier concentrations we are considering. We would like to point out that including Auger recombination in our system will cause a slight modification to the steady-state photo-carrier concentration and heating to the lattice through a multi-phonon emission process. The modification of the photo-carrier concentration is not expected to alter the many-body effect driven optical carrier cooling qualitatively. In addition, the heat dissipated to the lattice by any left-over high-energy excited-state carriers in an Auger recombination process will be completely absorbed by the external heat bath to maintain a fixed lattice temperature.

4.3 FY08

For Bloch oscillations and dynamical localization, we study the time-dependent and steady-state currents as well as a long-time average current in a strong nonlinear DC and AC electric field for an electron gas in a 1D quantum-dot superlattice. A microscopic model is employed for the scattering of electrons by phonons and static impurities within the frame of the Boltzmann equation. Our results demonstrate different roles played by elastic and inelastic scattering on the damped Bloch oscillations and the nonlinear steady-state current as well as their opposite roles on the damped dynamical localization. We also find a suppression of dynamical localization by strong Bloch oscillations and new features in the Esaki-Tsu peaks under a nonzero AC electric field in the presence of electron scattering. For optical probing of Bloch oscillations, the coupled optical Bloch-Boltzmann equations are employed to establish a general formalism for the optical response of current-driven electrons. We apply our theory in the linear and nonlinear regimes to a quantum dot superlattice (QDS). The DC-field dependences of both the peak energy and peak strength in the absorption spectrum for a QDS are calculated. We have found that both the peak energy and its strength are significantly reduced with increasing DC field, and the peak energy and peak strength are enhanced anomalously by raising the temperature for the nonlinear transport of electrons under a strong DC electric field. The control of the optical absorption through a bias field, which has been demonstrated in the numerical results of our calculations, can be applied in designing ultra-fast optical modulators and tunable filters in the THz frequency range.

Based on the coupled density and energy balance equations, we proposed a dynamical model for exploring many-body effects on optical carrier cooling in steady state. We have found that the dynamical carrier-cooling process is mediated by a photo-induced non-thermal electron-hole composite plasma in an intrinsic semiconductor under a thermal contact with a low-temperature external heat bath. The important roles played by the many-body effects, such as bandgap renormalization, screening and excitonic interaction, are fully included and analyzed by calculating the optical absorption coefficient, spontaneous emission spectrum and thermal energy exchange through carrier-phonon scattering. Both the optical carrier cooling and heating are found with increasing pump laser intensity when the laser photon energy is set below and above

the bandgap of an intrinsic semiconductor. In addition, the switching from carrier cooling to carrier heating is predicted when the frequency detuning of a pump laser changes from below the bandgap to above the bandgap.

We developed a dual-charged-fluid model for studying the steady-state transport of surface-acoustic-wave (SAW) dragged photocurrents of one-dimensional (1D) confined-state carriers. This model includes the effects of the quantum confinement and the tunneling escape of SAW-dragged 1D carriers, as well as the effects of the inelastic capture of two-dimensional continuous-state carriers and the self-consistent space-charge field. The numerical results uncover a high photocurrent gain due to suppressed recombination of 1D carriers in a region between an absorption strip and a surface gate. Based on this model, responsivities for the SAW-dragged photocurrents in a quantum well are calculated as functions of the gate voltage, photon flux, SAW power and frequency, and temperature, respectively. A responsivity as high as 1000Amp/Watt is found for high gate voltages and SAW powers, as well as for low photon fluxes and SAW frequencies.

We study the effect of a tilted magnetic field B on the modulation of tunneling, the ballistic conductance, the ballistic electron-diffusion thermoelectric power, and the orbital magnetization is studied for tunnel-coupled ballistic double quantum wires. The magnetic field has a component B_y along the wires, and a component B_x perpendicular to the plane that contains both wires. We find that B_y alters the B_x-dependence of the electronic and transport properties drastically in the presence of interwire tunneling. The latter has been studied extensively in the literatures in the absence of B_y and is known to show many interesting transport properties. The presence of B_y causes the effective tunneling integral to oscillate continuously with sign changes and decay eventually for large B_y. The B_y-induced interwire tunnel coupling between different sublevels and the quenching of it under a large B_y were both observed experimentally by Thomas et al.

4.4 FY09

We obtained numerical results for steady-state and time-dependent currents as well as for a long-time average current in strong nonlinear dc and ac electric fields for an electron gas in a one-dimensional quantum-dot superlattice. A microscopic model was employed for the scattering of electrons by phonons and static impurities by means of the Boltzmann equation method. The dc results were favorably compared with recent exact analytic results based on a relaxation-time model for electron-phonon scattering. Our results demonstrated the different roles played by elastic and inelastic scattering on the damped Bloch oscillations as well as the nonlinear steady-state current and their opposite roles on the damped dynamical localization. We also found a suppression of dynamical localization by strong Bloch oscillations and features in the Esaki-Tsu peaks in the presence of an ac electric field when electron scattering was included. On the basis of a nonequilibrium electron distribution obtained from the Boltzmann equation, a self-consistent-field approach was employed to establish a general formalism for the optical

response of current-driven electrons in both the linear and nonlinear regimes to a 1D quantum-dot superlattice. The dc-field dependences of both the peak energy and peak strength in the absorption spectrum for a 1D quantum-dot superlattice were calculated, from which we found: (1) both the peak energy and its strength were significantly reduced with increasing dc electric field; and (2) the peak energy and peak strength were anomalously enhanced by raising the temperature for the nonlinear transport of electrons when a strong dc electric field was applied.

The coupled force-balance and scattering equations were derived and applied to study nonlinear transport of electrons subjected to a strong dc electric field in an elastic-scattering-limited quantum wire. Numerical results demonstrated both field-induced heating-up and cooling-down behaviors in the non-equilibrium part of the total electron-distribution function by varying the impurity density or the width of the quantum wire. The asymmetric distribution function that was obtained in momentum space invalidates the application of the energy-balance equation to our quantum-wire system in the center-of-mass frame. The experimentally observed suppression of mobility by a driving field for the center-of-mass motion in the quantum-wire system was reproduced [see K. Tsubaki et al., Electr. Lett. **24**, 1267 (1988); M. Hauser et al., Sci. Technol. **9**, 951 (1994)]. In addition, the thermal enhancement of mobility in the elastic-scattering-limited system was demonstrated, in accordance with a similar prediction made for graphene nanoribbons [see T. Fang et al., Phys. Rev. B **78**, 205403 (2008)]. This thermal enhancement was found to play a more and more significant role with higher lattice temperature and becomes stronger for a low-driving field.

We exactly solved the Boltzmann equation for nonlinear electron transport in a quantum wire when impurity and phonon scattering coexist. Based on the calculated non-equilibrium distribution of electrons in momentum space, the scattering effects on both the non-differential and differential mobilities of electrons as functions of temperature and dc field were demonstrated. The non-differential mobility of electrons switches from a linearly increasing function of temperature to a parabolic-like temperature dependence as the quantum wire is tuned from an impurity-dominated system to a phonon-dominated one [see T. Fang, et al., Phys. Rev. B **78**, 205403 (2008)]. In addition, we obtained a maximum in the dc-field dependence of the differential mobility of electrons. The low-field differential mobility is dominated by impurity scattering, whereas the high-field differential mobility is limited by phonon scattering [see M. Hauser, et al., Semicond. Sci. Technol. **9**, 951 (1994)]. Once a quantum wire is dominated by elastic scattering, the peak of the momentum-space distribution function becomes sharpened and both tails of the equilibrium electron distribution centered at the Fermi edges are raised by the dc field after a redistribution of the electrons is fulfilled in a symmetric way. If a quantum wire is dominated by inelastic scattering, on the other hand, the peak of the momentum-space distribution function is unchanged while both shoulders centered at the Fermi edges shift leftward correspondingly with increasing dc field through an asymmetric redistribution of the electrons [see C. Wirner, et al., Phys. Rev. Lett. **70**, 2609 (1993)].

We also investigated the effects of the spin–orbit interaction (SOI) and a plane-perpendicular magnetic field on the conductivity of a two-dimensional electron system in the presence of a

one-dimensional electrostatic modulation. The calculations were performed when a low-intensity, low-frequency external electric field was applied. The Kubo formula for the conductivity was employed in the calculation. The single-particle eigenstates which depend on the strengths of the magnetic field, the SOI and the modulation potential, were calculated and then used to determine the conductivity. We obtained numerical results for the conductivity along the channels as well as the tunneling conductivity perpendicular to the constrictions as functions of the modulation potential, the SOI, and the magnetic field. We demonstrated that the effect of finite frequency is related to the reduction of both the longitudinal and transverse conductivities.

4.5 FY10

We calculated the surface response function and the image potential of a system of layered two-dimensional (2D) electron gas structures. A point charge was placed at a distance away from the surface which lies in the *xy*-plane. These 2D layers were coupled through the Coulomb interaction and there was no interlayer electron hopping. The separation between adjacent layers was adjusted to investigate the roles which the layer separation and the number of layers play on both the surface response function and the image potential. Specifically, we considered the system composed of graphene layers or the layered 2D electron gas (EG) formed at the interface of a semiconductor heterostructure such as GaAs/AlGaAs. We showed that the image potential for graphene is qualitatively the same as for the 2DEG. We examined the way in which the image potential was modified by applying a one-dimensional (1D) periodic electrostatic potential (through a gated grating for modulation). The results indicated that the charge screening for graphene was not much different than in the 2DEG.

We investigated the effects of the spin–orbit interaction (SOI) and a plane-perpendicular magnetic field on the conductivity of a 2D electron system in the presence of a 1D electrostatic modulation. The calculations were performed when a low-intensity, low-frequency external electric field was applied. The Kubo formula for the conductivity was employed in the calculation. The single-particle eigenstates which depend on the strengths of the magnetic field, the SOI and modulation potential, were calculated and then used to determine the conductivity. We obtained numerical results for the conductivity along the channels as well as the tunneling conductivity perpendicular to the constrictions as functions of the modulation potential, the SOI and the magnetic field. We demonstrated that the effect of finite frequency was related to the reduction of both the longitudinal and transverse conductivities.

We calculated the energy eigenvalues, the spin-split excitation gap (energy separation between the spin-triplet excited state and the spin-singlet ground state) and the concurrence for two interacting electrons captured in a quantum dot (QD) formed by a gigahertz electron pump which was modeled by harmonic confining potentials. From our calculations we found a peak in the QD size dependence of the energy level for the spin-singlet ground state, indicating the effect due to Coulomb blockade. In addition, we observed a local minimum in the QD size dependence

of the spin-split excitation gap for a relatively narrow quasi-1D channel formed from an etched wire, but a strong positive peak for the spin-split excitation gap in its QD size dependence with a relatively wide 1D channel. From the existence of a robust spin-split excitation gap against both thermal fluctuation due to finite (low) temperatures and the nonadiabatic effect due to fast barrier variations, we predicted a spin-entangled electron pair inside the QD with a weak coupling to external leads. An interference-type experiment which employed a gate-controlled electron pump and a beam splitter was proposed to verify this prediction. For the electron pump, a sinusoidal radio-frequency signal was applied to the entrance gate of a two-gated system over a narrow channel etched in a GaAs/AlGaAs heterostructure, where the measured current within the channel showed plateaus at Nef with $N = 1, 2, \ldots$ being the number of captured electrons in a QD and f the frequency of the sinusoidal signal.

Finally, we studied the Klein paradox in zigzag (ZNR) and anti-zigzag (AZNR) graphene nanoribbons. Due to the fact that ZNR (the number of lattice sites across the nanoribbon = N is even) and AZNR (N is odd) configurations are indistinguishable when treated by the Dirac equation, we supplemented the model with a pseudo-parity operator whose eigenvalues correctly depend on the sublattice wavefunctions for the number of carbon atoms across the ribbon, in agreement with the tight-binding model. We showed that the Klein tunneling in zigzag nanoribbons is related to conservation of the pseudo-parity rather than pseudo-spin as in infinite graphene. The perfect transmission in the case of head-on incidence was replaced by perfect transmission at the center of the ribbon and the chirality was interpreted as the projection of the pseudo-parity on momentum at different corners of the Brillouin zone.

4.6 FY11 & FY12

Epitaxially grown multi-layer graphene (MLG) may become a valuable and relatively cheap alternative to rather expensive exfoliated graphene. Recent angle-resolved photoemission spectroscopy (ARPES) experiments unambiguously demonstrated almost perfect Dirac cones on most of the layers. That is the electrons in the layers behave as if the layers are uncoupled in contrast to Bernal stacking in bi-layer graphene. Although some layers may establish bi-layer structures, the interaction between the first and the buffer layer (the one sitting on top of the SiC substrate) is always weak. The spectral function of MLG on SiC substrate suggests the energy gap is a few hundred meV. However the exact gap opening mechanism in epitaxial graphene is still under debate. The complexity comes from the fact that the graphene sample sits on top of a buffer layer which provides an additional mid-gap level, thus obscuring the exact energy dispersion curve and requires numerical *ab-* initio calculations. In addition, the density of states around the Fermi energy failed to indicate the gap. This ambiguity stimulated discussion regarding the symmetry-breaking gap versus the effects due to electron-electron interaction. This also indicates the importance of alternative techniques capable of identifying the induced gap by a buffer layer on a substrate. Electron energy loss spectroscopy (EELS) may be employed to ascertain the plasmon frequencies in

single and double layer graphene. The Raman shift of the inelastically-scattered electrons provides both particle-hole and plasmon excitation frequencies, which are usually characterized by their spectral weight, a quantity that depends on the transferred energy and in-plane momentum. This allows mapping of the plasmon dispersions.

We have developed a formalism and produced numerical results for the energy loss of a heavy and charged particle scattered at an arbitrary angle from epitaxially grown MLG. We compared these results with that of free-standing graphene layers. Specifically, we investigated the effect of the substrate-induced energy gap on one of the layers. The gap yields collective plasma oscillations whose characteristics are qualitatively and quantitatively different from those produced by Dirac fermions in gapless graphene. The range of wave numbers for undamped self-sustaining plasmons is increased as the gap is increased, thereby substantially increasing and red-shifting the MLG stopping power for some range of charged particle velocity. We investigated the role played by a gap in the energy dispersion on the absorption spectra of single and double layer configurations. All velocity regimes for the external charged particle moving perpendicular to the graphene surface were investigated. The plasmon pole approximation for the polarization agrees well with the results obtained with the full polarization in the random-phase approximation in the high-velocity regime only. The speed of the external charged particle determines whether the plasmon or particle-hole excitations dominate the scattering process. Consequently, since gapped graphene has a different plasma excitation spectrum than free-standing graphene, its stopping power may carry distinct signatures of the substrate induced gap. We also demonstrated that this formalism can qualitatively describe experimental data of EELS. It also allowed us to interpret the observed linear plasmon dispersion as coming from the acoustic undamped branch in double-layer graphene.

As an alternative to refractive lensing, there has been much interest in shaping the spatial distribution of the intensity of transmitted light in a region on the order of a wavelength through a metal film pierced with slits with subwavelength dimensions. In geometric optics a double-convex shaped thin dielectric lens is usually employed to focus the incident light. The focal length f is determined by $1/f \approx 2(n_r - 1)/R$, where n_r is the refractive index of the lens material and R is the radius of curvature of the lens surfaces. Therefore, the focal length increases with R. In the limit $R \to \infty$, we see that $f = \infty$, i.e., there is no focusing on the viewer side. This argument applies only to far-field light. However, near-field light with p polarization, which excites surface plasmons localized near a metal/dielectric interface, can still be focused by a planar metallic film containing a one-dimensional slit array with either variable slit width or variable slit dielectric material. For a non-smooth surface with sharp corners, such as a one-dimensional periodic slit array, the Green's function method cannot be applied. However, the partial-domain method used in the Green's function theory can still be employed in combination with the discrete slit-eigenmode expansion, as well as with continuous Fourier expansion methods, where the material property is assumed homogenous within a spatial domain. As a result, the previous single-slit approach can be generalized to

treat an arbitrary slit array. If a single slit is replaced by double slits in a periodic array, each surface-plasmon branch will be split into two, with a minigap controlled by electromagnetic coupling between the two slits.

We have derived a two-dimensional model for the diffraction of a plane electromagnetic wave by a perfectly electrically conducting metal film with a very large conductivity, which is pierced with slits of variable width, separation, and dielectric material. The solutions of the two-dimensional Helmholtz equation in different partial domains are matched to each other by proper boundary conditions for both perfectly electrically conducting metal and slit dielectric medium. This method has applications in modeling surface waves, optical beam steering, and metamaterial design. The use of a perfectly electrically conducting material for the slit side walls precludes modeling dissipation but allows for simple eigenmode expressions for the slit fields. If the optical depth of a metallic film is small and energy dissipation is not a consideration (for example, off-resonance in the visible frequency range), the use of a perfectly electrically conducting partial domain model is expected to be a good approximation. We applied our model to study the physics of the focusing of a normally-incident p-polarized plane electromagnetic wave after it has passed through a finite slit array in a thin metal film with a quadratic slit-width variation and a convex pattern of refractive index inside the slits. We compared different effects of the slit-width variation and convex quadratic refractive index pattern for both transmitted and reflected electromagnetic waves. We also investigated different features of the distribution of a transmitted electromagnetic wave in the near (closer than λ), intermediate (comparable to λ), and far (much larger than λ) field ranges. With this model we investigated the interference of evanescent waves generated from multi-slits in the near-field region, anomalous light bending in the optical frequency regime due to a negative dielectric function of a metal film pierced with slits, and the strong near-field focusing of an incident plane electromagnetic wave by a planar metallic film pierced with a slit array having a nonuniform slit dielectric material.

5. Conclusions

In this project, we have developed a force balance equation to describe the high-field nonlinear transport of hot-carriers in the absence of optical coherence. We have coupled the force balance equation with a Fokker-Planck equation, including optical dissipation, to describe high-field nonlinear transport of hot-electrons interacting with an intense optical field. We have developed a Boltzmann scattering equation to describe ultrafast scattering of hot-carriers with phonons, impurities, defects and other carriers after excited by an optical field. This allowed us to demonstrate that a second-order expansion of the scattering equation results in the Fokker-Planck formalism. We used a simplified version of the Boltzmann scattering equation, plus an energy-balance equation, to study photoluminescent cooling of semiconductors. We coupled the Boltzmann scattering equation (relative motion) with the force balance equation (center-of-mass

motion). Then, using momentum dissipation for the frictional forces allowed us to include carrier heating without the need to introduce electron and lattice temperature definitions for a quasi-equilibrium state, and it further allowed the description of the physical process for extreme non-equilibrium. We used a self-consistent-field approach to fully incorporate the many-body effects of electron screening, vertex correction, and exchange interaction in semiconductor Bloch equations, thus allowing us to study the dynamics/quantum kinetics of induced optical coherence in the presence of electron-impurity, electron-roughness, electron-phonon, and electron-electron scattering. Finally, we incorporated the effects of both carrier quantum kinetics and the force balance of photo-excited hot carriers into generalized semiconductor Bloch equations, thus allowing us to incorporate energy transfer between semi-classical carrier drift-diffusion under an electric field and quantum kinetics of interband/intersubband transitions. All of this was reported in the open literature in 25 papers and 22 presentations at international conferences.

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